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Technological challenges of seawater desalination: analysis of future opportunities

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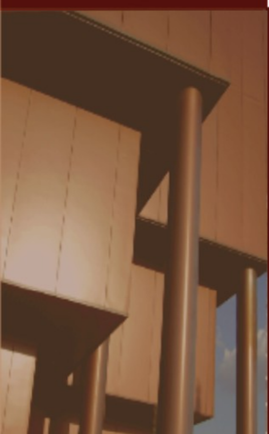

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1. Introduction

Close to 1/3 of the world´s population live in water scarce areas. Over 780 M people are still without access to improved sources of drinking water.

Seawater desalination is part of the solution to these water challenges and has been used now for decades to generate alternative water resources.

In order to make affordable drinking water obtained from seawater desalination, there has been a continuous optimisation of the process looking for more efficient solutions in terms of energy consumption.

In this regard, the use of thermal desalination technologies, such as Multi-Stage Flash distillation (MSF) and Multi-Effect Distillation (MED), has been changed in the last decades to Reverse Osmosis (RO) membrane technology because it requires less energy to desalinate seawater.

However, at the same time there has been a general trend of reviewing all industrial processes under sustainability criteria, that is, looking for more environmental friendly solutions, reducing the energy consumption and CO_2 emissions.

In this context, thermal desalination technologies have been considered again because of their conceptual advantage to be coupled with solar thermal energy, thus allowing for solar thermal-powered seawater desalination solutions.

Therefore, assessing the viability of coupling solar thermal energy with seawater thermal desalination technologies has been the first objective of this thesis, analysed in Chapter 1. A key factor in the analysis was the size of the plant, that is, the water production capacity (market opportunities) and the corresponding required power (the size of the solar plant). On top of that, thermal desalination technologies were also compared with reverse osmosis when both coupled with solar thermal-power.

Based on Chapter 1, for coupling with solar thermal energy all thermal desalination technologies where discarded except for very small-capacity seawater desalination systems.

Membrane Distillation (MD) technology may be potentially used in small-capacity systems due to the compactness, ability of dealing with highly concentrated saline solutions and its feasibility for operating at partial and variable loads. Seawater desalination based on MD was then analysed in Chapter 2 considering its current trends and future prospects.

The basic concepts of seawater desalination based on MD have been analysed. The existing MD configurations and pre-commercial and commercial MD systems have been reviewed. The performance of those systems have also been studied based on experimental data from tests performed by independent researchers. Having in mind other existing and well proven technologies, such as MED and RO, potential applications of MD technology in seawater desalination have been assessed. While the limited production capacity could be improved by advanced MD configurations, the low energy efficiency of the process may be a real barrier for MD technology. The most promising application of MD technology seems to be in brine concentration systems.

The use of conventional distillation systems (MED, MSF) have been rejected for seawater desalination (Chapter 1) and MD systems have inherent limitations such as low energy efficiency and small production capacity (Chapter 2). Therefore, RO systems are the reference technology for desalination processes in general and, in particular, when considering its combination with solar thermal power.

Having a deep understanding of RO technology is then important (Chapters 3 and 4) and is the technology in which to focus (Chapter 5) in order to improve seawater desalination. For RO Technology, the minimum theoretical Specific Energy Consumption (SEC) required for solvent extraction from standard seawater salt concentration, at recovery rates of 50% and the absolute minimum theoretical SEC required for recovery rate of 0% that is, obtaining only a drop of product water. Besides that, inefficiencies attributable to the status of membrane technology, to pumping inefficiencies, to plant configurations, etc, are calculated. Finally, the option of adopting innovative configurations reported in the literature is assessed in Chapter 3.

The core of the RO technology is the RO membrane, therefore the RO membrane modules are the key components. The design of SWRO membranes have been improved during the last decades coming to a standard design consisting in a module of typically 8 inches diameter and 1 meter long with spiral wounded flat sheets RO membranes. These RO membrane modules are placed inside a Pressure Vessel (PV) where a number of these modules can be installed in series. There are a number of phenomena, such as water and salt permeabilities, scaling, bio-fouling and concentration polarization that are inherent to the RO technology and to the fact that is based on the flow of the dissolvent through a membrane.

These phenomena depend on the membrane characteristics, module configuration, operating conditions (pressure and temperature) and the system configuration (recovery rate, number of membranes in serial), and have a direct impact on water production, product quality and energy consumption.

A thorough membrane performance model has been implemented (Chapter 4), including effects of pressure losses and concentration polarization at the feed-blowdown channel. This software calculates the water permeability and salts permeability from experimental data. Alternatively, this calculates salt concentration and flow of permeate from given design parameters of a specific membrane module.

Concerning a membrane serial, criteria of selecting the best membrane type for each position in the pressure vessel, depending on their permeability, have been reviewed. Membrane permeability should increase along the serial of membrane elements, having high rejection low energy elements in the first positions. In Canary Islands, two of those elements are enough to comply the required permeate quality. Besides that, the SEC reduces as the length of the series increases. The limiting factor is the product quality.

Finally, chapter 5 deals with a thorough analysis of innovative configurations with high prospects to achieve SEC decreasing. Not only configuration proposed in the literature are analysed, but also a patent pending innovation is proposed.

Chapter 1. SOLAR THERMAL-POWERED DESALINATION: A VIABLE SOLUTION FOR A POTENTIAL MARKET

This chapter has been published in the international journal *Desalination*, in a special issue on “Desalination using renewable energy” – volume 435 (June, 2018), pp. 60-69 – with the following title, authors and abstract:

Title: *Solar Thermal-Powered Desalination: A Viable Solution for a Potential Market*

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Abstract:

This paper deals with an assessment of solar thermal-powered desalination technologies in order to identify key issues for developing market opportunities. The topic of selecting the best solar desalination solution is analysed, case by case, considering different scenes: i) Rural communities with limited fresh water demand; ii) Regions with high demands of both, water and electricity and iii) Intermediate water demands. Detailed analyses of solar thermal-driven desalination – i.e. distillation and Reverse Osmosis (RO) - in comparison to solar PV/RO are presented. The quantitative assessment performed highlights that membrane distillation systems, when fully developed, will have market opportunities at very small-capacity seawater desalination systems. Besides that, dish concentrators coupled to micro gas turbines in case of limited water demand is a promising option. A single unit could produce about 10 m3/h of fresh water from seawater and several units could be coupled to drive the same desalination plant. Moreover, the only stand-alone systems with market opportunities for intermediate water production are based on reverse osmosis driven by parabolic troughs or linear Fresnel concentrators by means of organic Rankine Cycles. Finally, water demands over 25,000 m^3/d require both, a solar power plant and a reverse osmosis desalination plant.

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Chapter 2. SEAWATER DESALINATION BASED ON MEMBRANE DISTILLATION: CURRENT TRENDS AND FUTURE PROSPECTS

This chapter is a brief summary of the Master Thesis presented at the University of Seville in December, 2014. Main part of this chapter has been published (Buenaventura and García Rodríguez (2017).

8. CONCLUSIONS

The basic concepts of seawater desalination by means of MD have been studied. The existing MD configurations and pre-commercial and commercial MD systems have been reviewed. The performance of those systems have also been analysed based on experimental data from tests performed by independent researchers.

A detailed thermodynamic analysis of seawater desalination based on MD technology has been carried out to understand the physical phenomena, the driving forces of the process and to identify and quantify the theoretical limits of the technology. The main conclusions from this analysis are:

- Low energy efficiency of the conceptual process, since theoretical performance ratios (PR) at conventional operating conditions (T ≤85ºC) range from 6.5 to 8.7 (Table 2.2), in line to what has been tested for commercial available modules (Table 2.1), and far away from other thermal seawater desalination technologies such as MED, with actual PR> 8. If temperature gradient across the membrane as low as 5ºC is achieved, which is difficult due to the boiling point elevation (0.7ºC at 85ºC for seawater salinity – Fig.2.2 -), the theoretical limit is PR= 9.5.
- High potential of improving the existing MD systems, since it is a technology in development phase and most of the R&D efforts so far have been focused in the module design, but there is still a high potential of improving the system design. Temperature gradients across the membrane as low as 5ºC has been achieved, therefore increasing the efficiency up to PR of the order of 8-10 is possible.
- Limited production capacity of existing commercial products, as tested in commercial available modules with distillated fluxes in the range of 1 to 6.5 L/(h·m^2) (Table 2.1), far away from other membrane seawater desalination technologies such as RO (with average permeate fluxes in the range of 14 L/(h·m^2).
- High auxiliary energy consumption, as has been reported in literature and accordingly to high mass flow rate of seawater required to obtain unitary product flow.

While the limited production capacity could be improved by advanced MD configuration, the low energy efficiency of the process is a real barrier for MD technology.

Having in mind other existing and well proven technologies, such as MED and RO, potential applications of MD technology in seawater desalination have been assessed. The main conclusion is that for medium and large seawater desalination systems, the low energy efficiency and limited production capacity of MD technology make it not competitive at all. On the other hand, the technology may be applied for small seawater desalination systems where the two handicaps of MD technology may be irrelevant compared to other advantages it has, such as simple pretreatment and process control, low maintenance requirements and its conceptual ability to be coupled with solar thermal energy. Thus, a specific application of MD technology would be small autonomous solar thermal seawater desalination systems but competing with PV or wind powered RO seawater desalination systems.

For small and medium size seawater desalination systems where Zero Liquid Discharge (ZLD) is demanded, MD technology offers the possibility to concentrate the brine coming from the desalination plant to levels that other technologies can not simply reach. However, this application of MD technology is not recommended.

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Chapter 3. BASIC CONCEPTS ON SEAWATER REVERSE OSMOSIS DESALINATION

A summary of this chapter will be submitted for publication to the international journal *Desalination* with the following authors, title and abstract:

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Title: *Sea Water Reverse Osmosis: Towards 1 kWh/m^3 of Specific Energy Consumption*

Chapter 4. ANALYSIS OF MEMBRANE ELEMENTS IN SERIAL CONNECTION

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Title: *SWRO membrane elements: simple modelling and assessment of cost evolution*

Chapter 5. ANALYSIS OF REVERSE OSMOSIS INNOVATIVE CONFIGURATIONS

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Title: *Assessment of innovative configurations in Sea Water Reverse Osmosis Desalination*

Chapter 6. CONCLUSIONS

The main conclusions with regard to viable solutions for a potential market of solar thermal-powered desalination are reported in the first four conclusions, based on a comparative analysis of all desalination technologies. All of them, except Membrane Distillation (MD) are fully developed. Thus, only MD requires a thorough assessment of its technical limitations and potential improvements. A detailed thermodynamic analysis of seawater desalination based on MD technology has been carried out to understand the physical phenomena, the driving forces of the process and to identify and quantify the theoretical limits of the technology. Conclusions 4 and 5 summarise key points of the assessment performed. Reverse Osmosis (RO) is the most efficient desalination technology and the most suitable for both, conventional and renewable energy driven systems. The first question to answer is if a Specific Energy Consumption (SEC) of 1 kWh/m^3 is achievable. To this end a theoretical assessment of all potential options described in the literature are assessed. Besides that, a simulation model for preliminary design was developed. As a result of the thorough analysis of innovative configurations described so far, an innovative configuration is proposed that is patent pending. Points 6 to 12 report on conclusions related to SWRO desalination technology.

Main conclusions and recommendations are as follows:

1. Concerning solar desalination, conventional distillation processes for seawater desalination, namely multi-effect distillation and multi-stage flash distillation, exhibit too high solar energy consumption to compete with solar thermal-driven reverse osmosis. Moreover, discontinuous operation is not suitable for such technologies. Therefore, the use of conventional distillation processes is rejected in all cases, in particular when integrated into the thermal-cycle of a conventional solar power plant.

2. For market opportunities up to about 20.000 m^3/d, the only stand-alone solar thermal-powered desalination systems that may be considered are based on reverse osmosis driven by either:
    - Parabolic troughs or linear Fresnel concentrators by means of organic Rankine Cycles.
    - Dish concentrators coupled to micro gas turbines in case of limited water demand. A single unit could produce about 10 m^3/h of fresh water from seawater. Besides, several units could be coupled to drive the same desalination plant.

The main advantage of first option in comparison to stand-alone PhotoVoltaic (PV)-RO desalination is the possible use of thermal storage instead of batteries. Fire-boilers are not recommended as energy backup for solar organic Rankine Cycles due to the relatively low efficiency. Besides that, solar micro gas turbines have the advantage of the availability of heat rejection, which allows the Zero Liquid Discharge (ZLD) concept. Finally, they can be powered at night with conventional fossil fuels if necessary. Anyhow, for stand-alone desalination systems with energy backup, PV-RO desalination would always be more competitive than solar thermal-powered desalination systems.

3. Solar desalination for higher water demands require a large scale solar power plant and a reverse osmosis desalination plant. The concept of finding a global balance between consumption of electricity by the water production facility and the solar electricity generation is recommended, instead of the traditional concept of integrating both processes within the same plant. Besides that, the solar power plant technology, location and production should be adapted to the convenience of CAPital EXpenses (CAPEX) and OPEration EXpenses (OPEX). In addition, distributed fresh water production could also be considered if orography and distance between water demand locations make it necessary.

4. For medium and large seawater desalination systems, the low energy efficiency and limited production capacity of MD technology make it not competitive at all:
    - Temperature gradients across the membrane as low as 5ºC has been achieved, therefore increasing the efficiency up to PR of the order of 8-10 is possible – i.e. energy consumption greater than 230 kJ/kg -.
    - Limited production capacity of existing commercial products, as tested in commercial available modules with distillated fluxes in the range of 1 L/(h·m^2) to 6.5 L/(h·m^2), far away from other membrane seawater desalination technologies such as RO (with average permeate fluxes in the range of 14 L/(h·m^2).
    - High auxiliary energy consumption, as has been reported in literature and accordingly to high mass flow rate of seawater required to obtain unitary product flow.

5. On the other hand, the technology may be applied for small seawater desalination systems were the two handicaps of MD technology may be irrelevant compared to other advantages it has, such as simple pretreatment and process control, low maintenance requirements and its conceptual ability to be coupled with solar thermal energy. Thus, a specific application of MD technology would be small autonomous

solar thermal seawater desalination systems but competing with PV or wind powered RO seawater desalination systems.

6. Concerning modelling of SWRO desalination plants:
   - A simulation model with ERI-PX energy recovery device has been develop to carry out precise evaluation of the SEC considering only the productive core of a SWRO plant. The membrane skid is modelled with global parameters, namely, global pressure losses and net driving pressure at the tail of the membrane serial.
   - A thorough model of membrane series based on permeability coefficients of salt and water and empirical models of pressure losses and polarization effects was also developed Results on permeate flow, salinity and boron concentration along with recovery rate and pressure losses were validated by means of ROSA 9.1 software.

7. For RO Technology:

   - For a conventional SWRO configuration and working conditions of standard seawater at 25ºC and 48% of recovery rate, the SEC represents up to 2.3 kWh/m^3, considering 80% efficiency of the high pressure pump and 95% efficiency of the energy recovery. Around a 47% of the SEC in this case is attributable to the thermodynamic limit of the solvent extraction process and the other 53% to the configuration and real systems inefficiencies, being 0.38 and 0.86 kWh/m^3, respectively. Besides that, main inefficiencies are due to the high pressure pump, 0.53 kWh/m^3 (23%). Conventional configuration with ideal components represents 1.46 kWh/m^3, which corresponds to the technical limit with the current status.
   - The potential effect on the SEC of future improvements on membrane technology has been analysed and quantify to be lower than 0.19 kWh/m^3 (8%).
   - Regarding SWRO desalination with two stages, the benefits on the SEC have been analysed in this work for a wide range of temperatures, seawater salinities, recovery rates and pumping efficiencies. The influence of the second stage increases with recovery rate and feed salinity. For aforementioned conditions, the SEC goes down up to 1.97 kWh/m^3, being 0.34 kWh/m^3 (15%) the energy saving. Moreover, if operating with 60% of recovery rate is reliable, around 0.6-0.8 kWh/m^3 could be the energy saving attributable to a second stage (representing a reduction of 27 %).

   - Theoretically, PRO concept could be coupled to a conventional SWRO plant as an additional energy recovery device if an aqueous solution to be rejected is available. Up to 0.45-0.55 kWh/m^3 (20%) of energy saving could be theoretically achievable.

8. Considering energy efficient high pressure pumps, plant configuration has the most relevant effect on SEC. Therefore innovative configurations with the best prospects to allow SEC decreasing were identified and analysed. These innovative configurations were proposed by Veolia, GE and Desalitech.

9. The balance between CAPEX and OPEX seems to be better in conventional configuration than in that proposed by Veolia. However, Veolia´s configuration might be useful in improving fouling and scaling performance. In relation to fouling, in future development of RO membranes with high permeability this configuration may be essential to prevent excessive flux while maintain adequate average flux in order to achieve cost-effective configurations. Moreover, Veolia´s concept is useful if the compliance of product quality requires relatively high pressure due to either, high feed salinity or high temperature.

10. The innovative configuration proposed by GE allows CAPEX decreasing if pressure vessels with 9 membrane elements or even more are implemented. Moreover, next generation of RO membranes with higher permeability than that of current technology could be adopted by using GE´s configuration since flux on the front positions can be limited by selecting suitable values of bypass flow.

11. The best innovative configuration to reduce the SEC is CCD-Desalitech, which allows up to 10% of SEC reduction in case of batch operation equivalent to with 4-stages. However, the adoption of this configuration results in very complex design of the energy recovery device, operation and control. Therefore, this configuration is not recommended for SWRO desalination plants.

12. A patent pending innovative configuration is proposed with interesting prospects of decreasing main and auxiliary energy needs. Main energy consumption for salinity 0.035 kg/kg and 25ºC could be:
    - 2.14 kWh/m^3 with recovery rate of 45%.
    - 2.74 kWh/m^3 for the case of salinity of 0.035 with recovery rate of 65%.

    They allow for energy saving of 7% and 22%, respectively. Besides, SEC of 3.15 kWh/m^3 would be achievable with seawater salinity of 0.050 with recovery of 50%. CAPEX goes up but the increase in complexity is limited. In addition, the proposed configuration is able to operate with seawater of high concentration as brine of distillation plants. There are no competing technologies. This configuration could be adopted in SWRO plants with two-stages or PRO systems, thus resulting in additional energy saving.